Heavy-flavor collectivity, light-flavor thermalization in high-energy nuclear collisions

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Abstract. Because its heavy mass, heavy-flavor hadrons provide an unique advantage as a early stage probe for high-energy nuclear collisions. We will present recent measurements of open-charm production at RHIC. We argue that due to dense and hot medium created at the earliest stage of Au+Au collisions at RHIC, the non-zero value of open-charm v_2, caused by frequent strong interactions, will be a clear evidence for light-flavor thermalization in such collisions. This is an important step towards the understanding of the partonic Equation of State at RHIC.

1. Introduction
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The purpose of the high-energy nuclear collision program at both Brookhaven National Laboratory (BNL) and CERN is to probe strongly interacting matter under extreme conditions, *i.e.* at high densities and temperatures. Naturally the search for the existence of a new form of matter - the matter with partonic equation of state (EOS) that colloquially called quark-gluon plasma - is the experimental focus of the program. It has been demonstrated that the flow measurement is one of the most powerful methods for studying partonic EOS in high-energy nuclear collisions. For recent reviews, see [1, 2] and references therein.

Here the term flow has two important aspects: (i) collectivity of produced hadrons and (ii) the local thermalization among these hadrons [3]. As long as there are interactions among constituents, collectivity of the matter will be developed provided that the distribution of matter density is inhomogeneous. When the interactions last long enough the system will eventually approach local equilibrium and hence develops hydrodynamic type flow. At the early stage of a high-energy nuclear collision, both the matter density and its gradient are large, therefore we expect the development of partonic collectivity - the collective motion of partons. The issues of partonic local equilibrium can be addressed by studying heavy-flavor (c-, b-quarks) collectivity. This is because the collisions that generate the collective motion for heavy-flavors will likely lead to thermalization among the light-flavors (u-, d-, s-quarks).

In this report, we will focus solely on the subject of heavy-flavor production and its physics implications. Note, for a hadron that contains a heavy quark, either c- or b-quark, we call it heavy-flavor hadron or sometimes heavy-flaor. For the rest of the hadrons we will use the term light-flavor hadron or light-flavor, in short. This paper is organized as follows: we will first discuss the event anisotropy parameter v_2 from light-flavor hadrons. Then we discuss the first results of the charm hadron production and open-charm v_2, as observed in the electron decayed channel at RHIC. A brief summary will be given at the end.

2. Elliptic flow v_2 – Evidence for partonic collectivity at RHIC

The measured elliptic flow v_2 from the minimum bias $Au + Au$ collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV for π, K_S^0, p, Λ [6, 7] are shown in Figure 1 (a). Respectively, from top to bottom, the dashed-lines represent the elliptic flow of $\pi, K, p, \Lambda, \Xi, \Omega$ from hydrodynamic calculations [8]. As one can see, in the low p_T region, the trends of v_2 are well reproduced by the hydrodynamic calculations. At higher p_T, the v_2 is found to be saturated and hydrodynamic results over-predict the data. While the baryons saturate at $p_T \geq 3$ GeV/c with $v_2 \sim 0.2$, mesons saturation starts earlier at lower values of v_2.
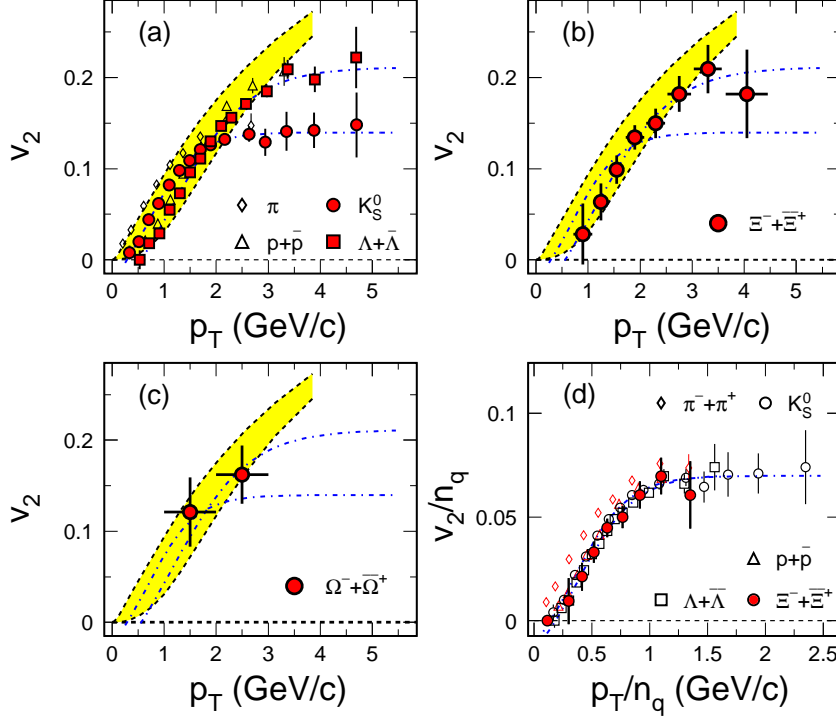

Figure 1. (a) Experimental results of the transverse momentum dependence of the event anisotropy parameters for π, K_S^0, $p+\overline{p}$, $\Lambda+\overline{\Lambda}$ [7, 6]. Hydrodynamic calculations are shown as thick-dashed-lines. From top to bottom are the results for π, K, p, Λ, $\Xi^- + \overline{\Xi}^+$, and $\Omega^- + \overline{\Omega}^+$; Multi-strange baryon elliptic flow v_2 are shown in (b) for Ξ and (c) for Ω. Plots (b) and (c) are from preliminary STAR results [4, 9]. (d) Number of constituent quark (n_q) scaled v_2/n_q versus scaled p_T/n_q. All curves are from [10].

Figure 1 (b) and (c) show v_2 for the multi-strange baryons $\Xi^- + \overline{\Xi}^+$ and $\Omega^- + \overline{\Omega}^+$ [4, 9], respectively. Although they tend to suffer much less rescatterings during the later hadronic stage of the collisions [5], the values of v_2 for strange-baryons, within the experimental uncertainties, are found to be as high as other hadrons at a given p_T . Therefore, the v_2 must have been developed at an earlier stage prior to hadronization.

The number of constituent quark (NCQ) scaling fit results to K_S^0 and Λ are shown as dot-dashed lines in Fig. 1. According to coalescence approaches [13], after scaling both values of v_2 and p_T with the NCQ of the corresponding hadron, all particles should fall onto one single curve. Fig. 1(d) shows the scaled v_2 versus the scaled p_T. Indeed, with the exception of pions, all particles follow a single curve. Pions (open triangles) do not follow the scaling, because of a large fraction of pions produced through resonance decays. This observation implies that due to high parton density and intense interactions partons have already developed collective motion

in heavy ion collisions at RHIC.

The results of the multi-strange hadron v_2, the early freeze-out [5, 11, 12] for the multi-strange hadrons and the NCQ-scaling for all hadrons all point to the collectivity that has been developed prior to hadronization, therefore, constitute a clear piece of evidence for the development of partonic collectivity in $Au + Au$ collisions at RHIC.

3. Heavy-flavor collectivity - light-flavor thermalization at RHIC

In the previous sections, we established the evidence of partonic collectivity for light-flavor (u, d, s) hadrons. In order to access the partonic EOS, one must address the issue of early excitation/thermalization [15] of the system. Because the masses of heavy-flavors are much larger than the highest possible excitation of the system reached in $Au + Au$ collisions at RHIC, a large number of rescatteings would be required in order to develop any collective motion. Furthermore, since the number density of light-flavors is much higher than that of heavy-flavors, the intensity of rescattering should be even stronger among the light-flavors. As expected for any physical system, intensive rescattering among constituents will eventually lead to thermalization. Hence the heavy-flavor collectivity could be used to probe the intensity of partonic rescattering and therefore the degree of light-flavor thermalization. In practice, this means that we should measure the v_2 of charm-hadrons [10, 16, 17, 18, 19].
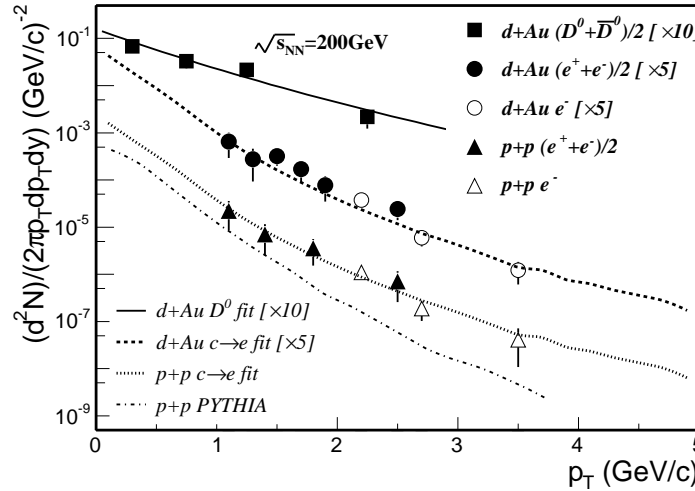

Figure 2. The transverse momentum distributions for reconstructed D^0 (squares) from $\sqrt{s_{NN}} = 200$ GeV $d + Au$ collisions, non-photonic electrons (filled-circles and triangles) from $d + Au$ collisions and $p + p$ collisions, respectively. The solid- and dashed-lines are the results of a common fit for both D^0 and electron spectra in $d + Au$ collisions. Scaled by the number of binary collisions in minimum bias $d + Au$ collisions, ($N_{bin} \approx 7.5$), the fit results (dotted-line) matches to the $p + p$ results (triangles) well. Pythia results for $\sqrt{s_{NN}}$ =200 GeV $p + p$ collisions are shown as dot-dashed-line.

The open-charm yields at mid-rapidity in $\sqrt{s_{NN}}$ =200 GeV $p + p$ and $d + Au$ and $\sqrt{s_{NN}}$ =130 GeV $Au+Au$ collisions have been measured via directly reconstructed and non-photonic electron decay channels [20, 21, 22, 23]. Recent results [20] are shown in Fig. 2. The shape of the p_T spectrum is a power-law, a characteristic feature of hard scattering in elementary reactions. In nucleus-nucleus collisions, on the other hand, the later stage rescatterings of both partonic and hadronic interactions, would modify the shape to a thermal like distributions [24]. A combined fit to the directed reconstructed D^0 meson and non-photonic electron spectra, shown as solid-

and dashed-lines in Fig. 2. The result mid-rapidity charm cross section per nucleon-nucleon collisions is:

$$d\sigma_{c\bar{c}}^{NN}/dy = 0.30 \pm 0.04(\text{stat.}) \pm 0.09(\text{syst.}) \quad (\text{mb})$$

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Using the rapidity width from Pythia calculation [25], the extrapolated total charm cross section is [20]:

$$\sigma_{c\bar{c}}^{NN} \approx 1410 \quad (\text{mb})$$

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This value is significantly larger than NLO pQCD predictions [26]. Those predictions seem to work well for elementary collisions up to $\sqrt{s_{\mathrm{NN}}} = 80$ GeV. Within the large uncertainties of both statistics and systematics, the results from STAR and PHENIX experiments [22] are consistent.
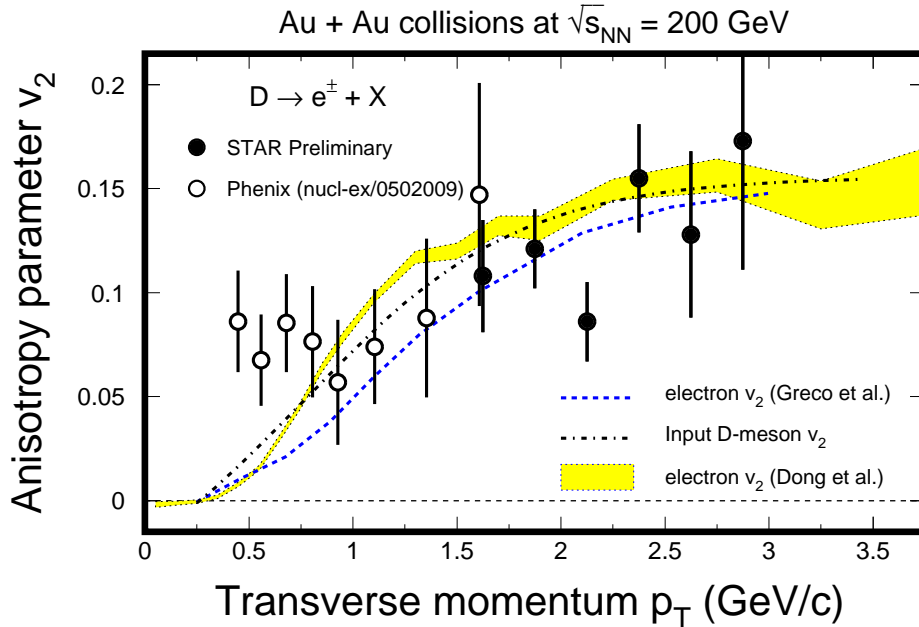

Figure 3. Non-photonic electron elliptic flow $v_2(p_T)$ from minimum bias $Au+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Data from PHENIX [27] and STAR [28] experiments are shown as open- and filled-circles, respectively. Only statistical errors are shown. Dashed-line and the hatched band are charm-hadron decayed electron $v_2(p_T)$ from refs. [10, 16].

The heavy-flavor program has just started at RHIC [20] and there is no measurement of v_2 with reconstructed charm-hadron yet. However, as discussed in [10, 16], the charm-hadron v_2 can be inferred by their decayed electron v_2. The results of the non-phonic electron v_2 from minimum bias $Au + Au$ collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV [27, 28] are shown in Figure 3. These non-photonic electrons are presumably from the decays of charm-hadrons. Only statistical errors are shown in the figure and the systematic errors are in the order of 25%. The dashed-line and hatched-band are charm-hadron decayed electrons from model calculations [16, 10]. The dot-dashed-line [10] is the D-meson v_2 assuming NCQ-scaling. Since there are several resonance states for charm-hadrons, hadronic interactions could also develop non-vanishing v_2 [17, 18]. A recent study based on the HSD model indeed shows the value of maximum v_2 in the order of 2-3% [17] in the b=7 fm $Au + Au$ collisions at RHIC. Due to the large statistical uncertainties in data, both

model results are consistent with the measurements. The observation indicates, if confirmed with (high statistics) reconstructed charm-hadron measurements, the onset of collectivity for the heavy-flavors and the light-flavor thermalization at RHIC.

4. Summary

In summary, we have presented the recent measurements of partonic collectivity, open-charm hadron p_T distributions, and the v_2 of non-photonic electrons from collisions at RHIC. The results of pQCD calculations, tuned for lower energy collisions, under-predict the RHIC production cross section, implying the collision energy dependence of the QCD model scales. These new experimental results present the beginning of an important program for high-energy nuclear collision: early stage partonic thermalization. We emphasize again that the charm-hadron measurements and the information of early thermalization are the final step towards the establishment of the quark-gluon-plasma EOS at RHIC.

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